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Procedia CIRP 18 (2014) 244 – 249

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International Conference on Manufacture of Lightweight Components – ManuLight2014

A Hybrid Flexible Sheet Forming Approach Towards Uniform Thickness Distribution

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Abstract

This paper presents a newly developed flexible sheet forming approach with better sheet thickness distribution and reduced processing time comparing to the conventional incremental sheet forming. In the approach, a two-step forming process has been proposed: multi-point forming as preforming is employed to achieve an initial shape and designed thickness distribution; After the preforming, incremental sheet forming process is then applied to finalize part geometry with desired thickness distribution. In the work, a numerical model for predicting the thickness distribution of the final part is developed by integrating finite element simulation and analytical prediction of ISF process. To achieve the uniformity of final thickness distribution, the preformed shape is optimized based on the developed thickness prediction model. Additionally, a real industrial case problem of forming an aerospace cowling is used to validate the proposed hybrid flexible sheet forming approach. Satisfactory results are obtained, which demonstrates the feasibility and effectiveness of the developed forming process.

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Keywords: Hybird forming; Incremental sheet forming; Thickness distribution

1. Introduction

Sheet metal forming has been widely used in automotive, aerospace, medical, and recently in renewable energy. The conventional sheet metal forming processes such as stamping and deep drawing are more suitable for mass production. For manufacturing of high value-added, small batch and customized products, the employment of conventional process would results high tooling costs, long lead time and high-energy consumption. To overcome these limitations, the flexible sheet forming concept, aiming to reduce the lead time, incurred cost and energy consumption, has attracted significant research attentions in recent years, incremental sheet forming (ISF) [1] and multi-point forming (MPF) [2] are two typical flexible sheet forming approaches.

Incremental sheet forming, with its unique technical advantages in dieless forming and enhanced formability, has attracted ever increasing interests in both academic and industrial communities after the popularity of NC technology in 1990s [3]. In the ISF process, a hemispherical tool moves along the pre-designed toolpath and deforms the clamped sheet layer by layer. With the inherent feature of localized deformation, ISF could achieve higher strains comparing to the traditional stamping process [4]. However, ISF also has some limitations including long processing time, low geometrical accuracy and coarse surface finish. In order to overcome these limitations, effort has been made to explore a number of variations of the ISF process：Iseki et al [1] developed the modern ISF process using a simple tool and a path of the contour line and a non-symmetrical parts has been made using a manually operated X-Y table. Matsubara [5] developed the two-point incremental forming (TPIF) process, in which the tool is drawing contours from the inside outwards while the blank holder is gradually moving downwards on to a male die. Bambach et al [6] employed a multi-pass strategies to formed a four–sided pyramid with a nearly right angle. Malhotra et al.[7] employed mixed in-out and out-in tool paths achieve a smoother component. Malhotra et al. [8] also developed a double side

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doi:10.1016/j.procir.2014.06.139

incremental forming (DSIF) process with two moving tools. In the DSIF process, the sheet is squeezed by two tools and uniform thickness distribution can be obtained. In the above ISF processes, the control of sheet thinning is difficult as the blank will not flow into the die cavity during the deformation as that in conventional stamping process. To overcome this problem, Araghi et al. [9] proposed a hybrid process in which the stretch forming and non-symmetric incremental sheet forming are combined together. Using this hybrid process, better sheet thickness distribution can be obtained with reduced forming time. However, the potential problem of the existing hybrid forming technology is that a specific supporting die is required, which reduced the process flexibility and efficiency. At present, there is limited report on this hybrid technology. Further development are necessary based on the existing ISF technology to improve this process.

Multi-point forming (MPF) is another flexible forming technology. In the multi-point forming process, matrices of punches are employed to replace the traditional dies [10]. In the multi-point forming, 3D freeform surface can be obtained by adjusting the position of the punches. However, in the MPF process, a particular defect is the dimples left by the punches, which is inevitable even by placing elastic rubber sheet on the die surface [11]. In addition, the shape complexity may be limited by the punches' size in MPF process. Due to above shortcomings, multi-point forming is more suitable for forming parts with small curvatures other than those with complex geometries.

In order to overcome the problems in the existing flexible forming processes, a hybrid flexible sheet forming approach has been proposed in this work by combining the MPF and ISF technology. In the approach, sheet is preformed to designed shape by employing the multi-point forming method. After the preforming, incremental sheet forming process is utilized to form the part from the concave side of sheet. In this way, the designed part geometry could be achieved with improved thickness distribution.

2. Flexible hybrid forming

2.1. Introduction to the flexible hybrid forming process

To facilitate the proposed flexible forming approach, a hybrid forming setup has been designed and developed as shown in Fig. 1. As can be seen in the figure, a forming platform with rotatable blank holder and reconfigurable die has been designed. By clamping the sheet in the blank holder, a preform operation can be implemented by moving the platform downwards. After the preforming process, the blank holder can be unclamped from the platform and rotate to the vertical position with the preformed part in it. Using an industrial robot, ISF process can be implemented from the concave side of the part. By using this process, the part could be finalized to the designed shape. The actual developed flexible hybrid forming equipment is shown in Fig 2.

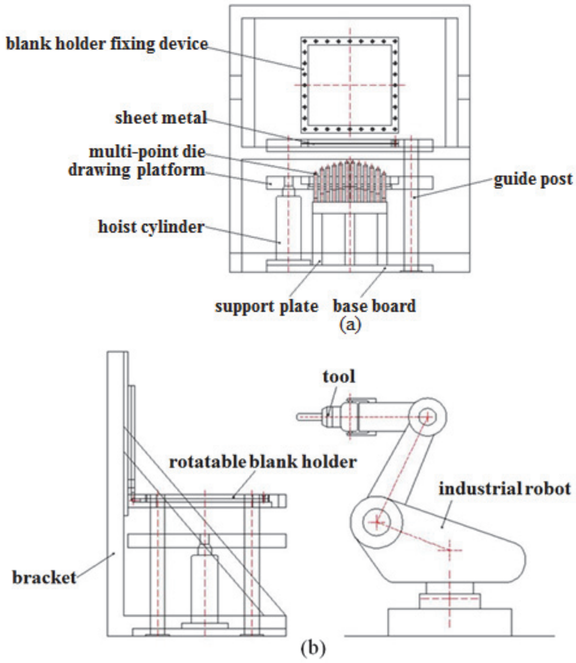

Fig. 1. Hybrid forming equipment: (a) Multi-point forming structure; (b) Incremental sheet forming structure

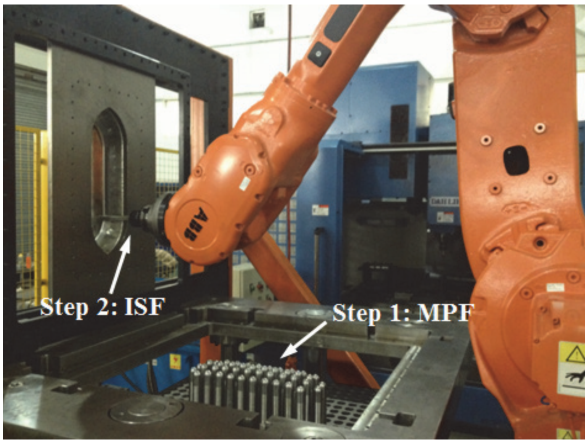

Fig. 2. Two-step hybrid flexible sheet forming equipment

In this two-step forming process, the challenge comes from the determination of preform shape to achieve a more uniform thickness. As preform shape is a major factor that affect the final part thickness, a proper preform shape become virtually important in the process design of the developed hybrid forming process. In order to predict the final thickness distribution, a numerical approach has been employed in the analysis. Based on the numerical model, optimisation could be implemented to improve the thickness distribution for the final part.

2.2. Thickness prediction model

The proposed flexible hybrid forming approach contains two forming steps: multi-point forming and sub-sequential incremental forming. The sheet thickness distribution after MPF process could be obtained by using the finite element (FE) method. In this work, ABAQUS explicit code has been employed to predict the preformed shape and the corresponding thickness distribution. For the ISF process, as ISF simulation is very time consuming, a geometrical approach would significantly improve the computational efficiency with satisfied accuracy at the same time. Concerning the part thickness prediction for the ISF process, Filice [12] proposed a model to predict the thickness distribution using the geometry shape parameter of the final produced parts in a double-pass incremental forming of a cylindrical cup. Bambach presented a geometric approach to predict the membrane strains and sheet thickness distribution under 2D conditions [13].

In this work, the commonly used sine law has been employed to predict the thickness distribution after the ISF step. As shown in Fig. 3, using the preform mesh with thickness attribute obtained from the FE simulation of preforming, the node on the preform mesh was projected along its normal direction to the model that representing the final shape of the part.

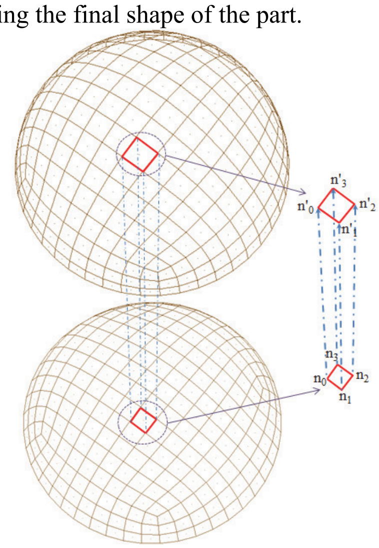

Fig. 3. Node projection between preform mesh and final mesh

2.3. Preform shape design

In the proposed two-step flexible hybrid forming process, the preform shape is a major factor that affects the thickness distribution of the final part. In this work, different preforming strategies including using different preform shapes as well as using multi-stage forming approaches are explored and how will these strategies affect the final preform shape are investigated.

An aerospace cowling, as shown in Fig 4, was employed in the investigation of the preform shape design. By examining the geometrical features of the cowling model, it can be found that it contains near hemisphere features at the two ends and vertical wall at the bottom half of the part. The total length of the cowling is 520mm with the width of 180mm and height of 130mm. The challenge of forming this part comes from the vertical wall, which is impossible to form solely using the incremental forming method. At the same time, it was found that it is also very difficult to form the part using the conventional deep drawing process in application, which is over the forming limit of the sheet material.

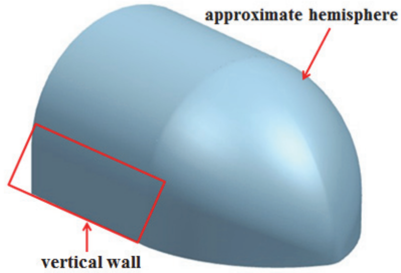

Fig. 4. Aerospace cowling model

AA1100 aluminum sheet with initial thickness of 1.0mm has been used to form this aerospace cowling. The flow stress of the AA1100 material was obtained by using the tensile test, as shown in Fig. 5. The Young's modulus is 68.9GPa.

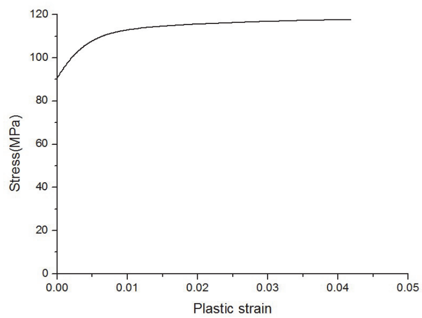

Fig. 5. Flow stress strain diagram

The preform step was simulated by using ABAQUS explicit code. The friction coefficient was set to 0.05 for the contacts between die and sheet. In order to increase the computational efficiency, only a quarter of the model was calculated in the simulation due to symmetry of the cowling model. Fig. 6 shows the FE model with thickness distribution after simulation. As can be seen in the figure, the minimum thickness occurs at the top of hemisphere.

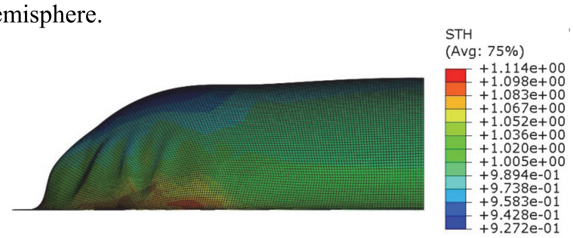

Fig. 6. Preform finite element model

In the incremental sheet forming process, the thinning increase with the wall angle and it is very difficult to form the vertical wall. The sheet thinning has a quite different tendency in the drawing process. In the process, the sheet at the top of hemisphere is under biaxial tensile stress condition, which undergoes maximum deformation. Using this different sheet deformation characteristic in preforming and incremental forming, the thickness distribution may be improved: in the first stage preforming process, the vertical wall and the part with large wall angles will be formed; in the second stage incremental forming process, the top half part will be formed. In this way, as shown in Fig. 7, deformation of the part will be both occur in preforming and incremental forming, which is ideally to obtain a part with more uniform thickness distribution.

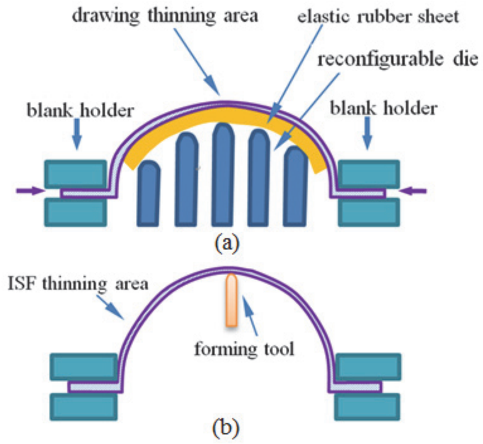

Fig. 7. Hybrid forming process: (a) Multi-point preforming; (b) Incremental sheet final forming

Fig. 8(a) & (b) shows two designed preform shape. As shown in Fig. 8(a), the first preform shape has similar shape with the final part; as shown in Fig. 8(b), the second preform shape was higher with inclined wall. In order to further improve the thickness distribution in the forming process, two-step forming approach is also employed in the analysis. Fig. 8(c) & (d) shows the designed preform shape for the two-step preforming approach, in which the first-step shape is lower and the second-step shape is the same with single step design given in Fig. 8(a) & (b).

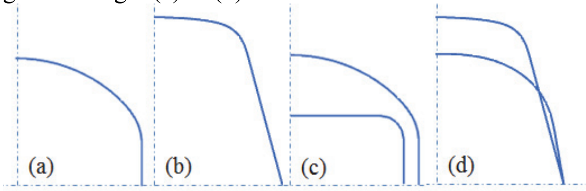

Fig. 8. (a) The first preform shape; (b) The second preform shape; (c) The first two-step preform shape; (d) The second two-step preform shape

Fig. 9 shows the predicted thickness distribution using the developed integrated numerical approach. As can be seen in the figure, the major thickness reduction occurs at the hemisphere end of the part. Using the proposed preform shape as given in Fig. 8(a), the minimum thickness of the final part is about 0.477mm and the thickness reduction is over 50%. By using the corresponding two-step preforming approach, there is a slight improvement for the final thickness distribution, with a minimum value of 0.501mm. Using a different preform design as given in Fig. 8 (b), the thickness distribution are improved with the minimum thickness of 0.630mm. By employing the corresponding two-step forming approach, the minimum thickness can be further increase to 0.654mm, as shown in Fig. 8 (d). By comparing the above preform design and predicted thickness distribution, it can be found that: 1) The thickness distribution of the final part is majorly affect by the preform shape. 2) The improvement of the thickness distribution of the part is limited by using the two-step preforming strategy. Thus is may not be cost effective to apply the two-step preforming strategy in the actual forming applications.

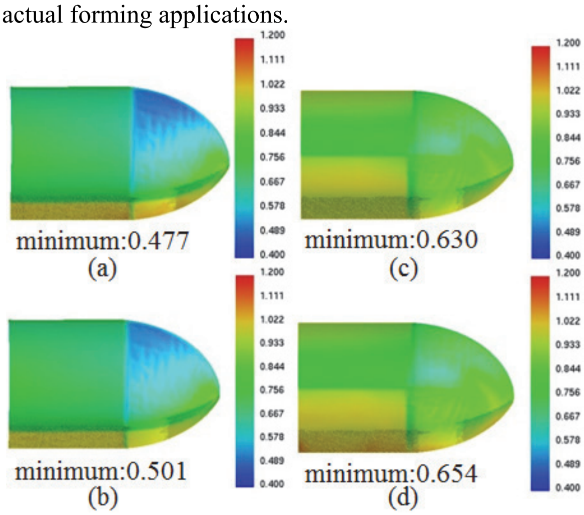

Fig. 9. (a) Thickness prediction with the first preform shape; (b) Thickness prediction with the second preform shape; (c) Thickness prediction with the first two-step preform shape; (d) Thickness prediction with the second two-step preform shape

2.4. Further preform shape optimization

In the previous section, the preform shape designs are presented and compared. To further improve thickness distribution, optimisation technology has been employed to optimized geometrical parameters of the initial preform shape design. In this work, the radius of the preform was optimized by using the conventional gradient-based search [14] method, which will affect the local shape of the preform design.

Fig. 10 shows the optimization result of the preform shape. As can be seen in the figures, after the optimization, the thinning are reduced on the part with large wall angles. The minimum thickness is improved from 0.619 to 0.630 after the optimization.

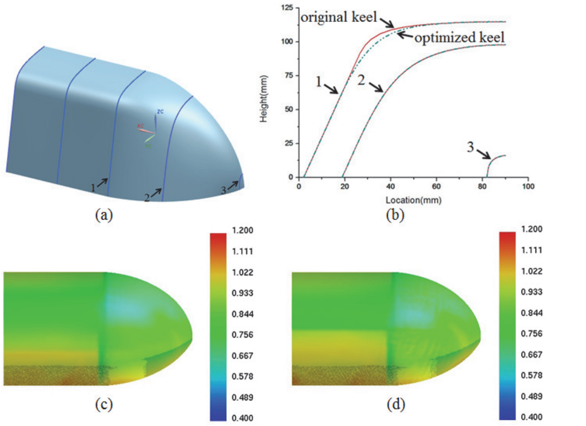

Fig. 10. (a) Preform shape design method; (b) Comparison between original keels and optimized keels; (c) Thickness prediction for original preform; (d) Thickness prediction for optimized preform;

3. Experiments

Using the flexible hybrid forming device developed, the cowlings are made according to validate the numerical prediction and designed preform shape. As the two-step drawing process has only limited impact on the final thickness distribution, only the signal pass preforming process is employed in the experiments. In the multi-point forming process, the multi-point die was configured to the deigned shape and then deformed the sheet with a constant die speed of about 3mm/s until reached the pre-calculated position. Fuchs RENOFORM oil was employed as lubricant been sheet and tools.

In the incremental forming process, the spiral tool path strategy with a constant scallop height of 0.01mm was employed to avoid a sudden change of the tool movement direction. Fig. 11 shows the generated tool path for the final incremental forming. The tool moving velocity is 5000mm/min. MoS2 powder mixed within lubricant grease was used for the lubricant between the tool and sheet. Fig. 12 shows the preform and the final formed cowling.

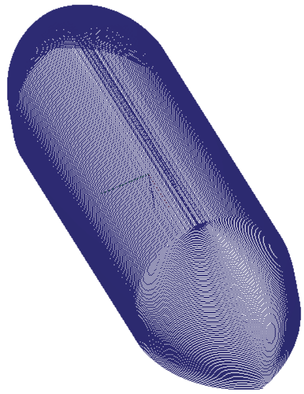

Fig. 11. Spiral incremental sheet forming toolpath

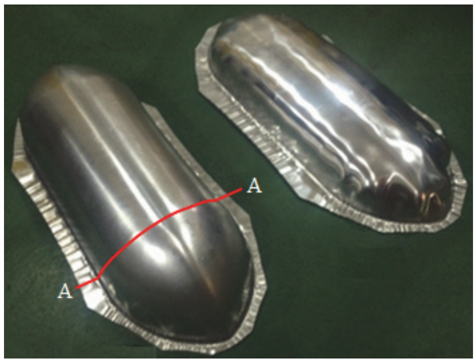

Fig. 12. Preform result(right) and final result(left)

To examine the final thickness distribution of the part, the formed parts are cut along the cross-section A-A as shown in Fig. 13. The thickness distribution along the section A-A are measured and compared with the predicted result. Fig. 13(a) shows the comparison results of the initial preform design while Fig. 13(b) shows the comparison results of the optimized preform design. As can be seen in Fig. 13(a), the predicted and experimental result shows the similar trend of thickness distribution of the final part. The maximum difference is about 0.15mm, which represent the difference of 15%. Concerning the thickness distribution of the initial design, there is an obvious thinning band at the inclined wall of the cowling. The minimum thickness is about 0.41mm. This thinning may be cause by the incremental sheet forming as the preform shape is not depth enough. Concerning the optimized shape design as shown in Fig.13 (b), the thickness prediction and the experimental results are quite close. The thinning band shown in Fig.13 (a) is much more improved. Although there is also a thickness drop on the part, the minimum thickness is raising to about 0.65mm. These results not only suggested the robustness of the numerical thickness prediction model, but also the efficiency of the proposed shape design optimization strategies.

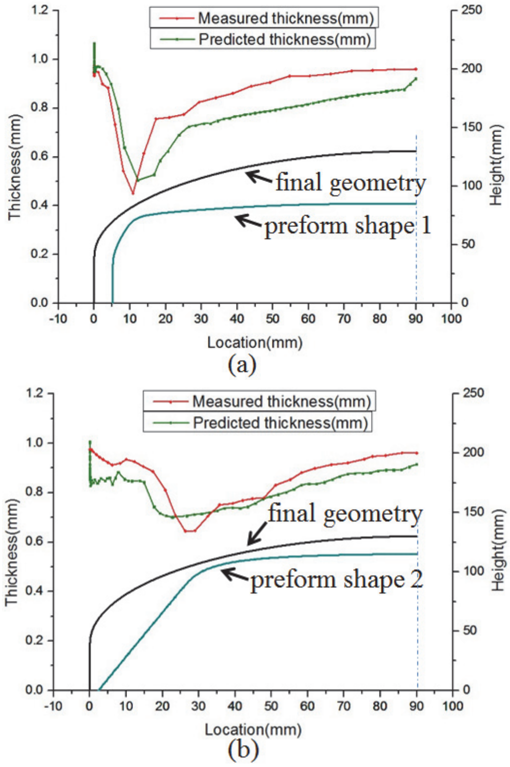

Fig. 13. (a) First preform shape results; (b) Second preform shape results

4. Discussion & conclusion

This work proposed a hybrid flexible forming process by combining the multi-point forming and incremental sheet forming, which overcomes the problems of uneven thickness distribution for final parts in conventional ISF process. In the paper, an integrated numerical thickness prediction model has been developed. Based on this model, different preform strategies including one-step and two-step preform method and different preform shapes have been tried and the best strategy has been selected. Case study for forming an aerospace cowling proved that with an appropriate preform design, thickness distribution of final part can be effectives improved in the proposed hybrid flexible forming approach. The conclusion of this work can be summarized as follows:

1) The proposed hybrid flexible forming method is an effective approach for forming of high-valued added, small batched and customized sheet metal products.

2) With a proper preform design, the thickness variation of final part can be much improved with reduced forming time comparing to the conventional ISF process which require multi forming passes.

3) A thickness prediction model with corresponding preform design & optimisation strategies have also presented, which was proven to be relatively accurate in experimental validation.

Concerning the future work, the present thickness prediction model for the ISF process is based on the sine law. Further research is necessary to enhance the thickness prediction accuracy. In addition, preform shape design still involved considerable manual interference. The design optimisation strategy may also need to be improved for the enhanced automation in the following research.

Acknowledgements

This research is partly supported by FP7-PEOPLE-2013-IIF project (628055).

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